DEPARTMENT OF THE AIR FORCE

HEADQUARTES, 603D REGIONAL SUPPORT GROUP (USAEF)

European Office of Aerospace Research and Development

(EOARD)

FINAL REPORT

Contract F61775-98-WE072

SPC 98-4032

Title of Project:	**Supersonic COIL Driven by a Jet Singlet Oxygen Generator**
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Date	25 June, 1999

AQF99-10-1858

REPORT DOCUMENTATION PAGE

Form Approved OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	25 June 1999	Final Report

4. TITLE AND SUBTITLE

Supersponic COIL Driven by a Jet Singlet Oxygen Generator

5. FUNDING NUMBERS

F61775-98-WE072

6. AUTHOR(S)

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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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8. PERFORMING ORGANIZATION REPORT NUMBER

N/A

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

EOARD
PSC 802 BOX 14
FPO 09499-0200

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

SPC 98-4032

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

A

13. ABSTRACT (Maximum 200 words)

This report results from a contract tasking Institute of Physics Academy of Sciences as follows: The contractor will complete the chemical oxygen-iodine laser (COIL) by adding newly fabricated components; test the operation of individual parts of the whole COIL system and attempt to optimize the operation of each of them; and test the completed device as a laser by determining the output power, the small signal gain, the saturation intensity, the optical extraction efficiency, and the chemical efficiency.

14. SUBJECT TERMS

EOARD, Chemical lasers, COIL

15. NUMBER OF PAGES

27

16. PRICE CODE

N/A

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19, SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UL

Settlement of the contract

The contractor will complete the chemical oxygen-iodine laser (COIL) by adding newly fabricated components, test the operation of individual parts of the whole COIL system and attempt to optimize the operation of each of them; and test the completed device as a laser by determining the output power, the small signal gain, the saturation intensity, the optical extraction efficiency, and the chemical efficiency.

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1. Introduction

A co-operation with the US AFRL/DE started by the Contract F61708-96-W0208 the 1st September 1996, and has followed by this contract. Both contracts have had to do with investigations in a supersonic Chemical Oxygen-Iodine Laser (COIL) driven by a jet singlet oxygen generator (jet SOG).

In the Institute of Physics of the Academy of Sciences, a small-scale 1 kW class supersonic COIL device has been developed according to an original design, and with several goals in mind:

- to be driven by a highly efficient jet SOG,
- to employ a close-loop flowing basic hydrogen peroxide (BHP) system with continuous cooling, which permits a longer run time (5-10 minutes) than usual in majority laboratories (several seconds),
- to construct a device as compact as possible, and minimize a loss of singlet delta oxygen ($O_2(^1\Delta_g)$) during its transport from generator to laser by minimizing the subsonic gas volume,
- to operate efficiently the laser at relatively high subsonic (generator) pressure (up to 70 Torr),
- to design a laser optical cavity with the gain length of 5 cm and slit supersonic nozzle to be comparable with a VertioCOIL - the COIL driven by the rotating disk SOG - developed at the USAF Research Laboratory,
- to use Helium as a primary (oxygen) and secondary (iodine) diluent and load-bearing gas,
- to compare parameters and laser characteristics after achieving an optimized COIL operation with the VertiCOIL characteristics.

A design, fabrication, installation, and testing of the individual parts of COIL device in the Institute of Physics proceeded according to the **Projects schedule.** During the lasting of this contract, the device undergone a significant modifications, and the COIL system was completed by adding newly fabricated components, for example, a multichannel data acquisition system with PC on-line, a primary helium injector, mass flow meters for chlorine and helium with analogue outputs, an originally designed iodine vaporizer, a new stainless steel supersonic

nozzle, and others. A number of minor device engineering improvements have been made to optimize a performance, for example, of the jet SOG, iodine concentration measurements, secondary helium flow, etc. A description of essential elements and subsystems parameters of the whole COIL device will be therefore presented first. **Some technical details and drawings can be found in previous Interim Reports of this contract sent to the EOARD.**

Project schedule

	1996	1997				1998				1999
	IX–XII	1.	2.	3.	4.	1.	2.	3.	4.	1. – 6.
Vacuum system:										
Upgrade, testing										
Generator:										
Handwork										
Design										
Fabrication										
Installation										
Testing										
Diagnostics:										
Installation										
Testing										
Laser:										
Handwork										
Design										
Fabrication										
Installation										
Testing										
Report										

2. Description of COIL device in the Institute of Physics

Singlet oxygen generator

Originally designed jet SOG is made of Plexiglas with the inner cross section of 50 x 48 mm. A gas-liquid counter flow reaction system was chosen with 10 or 15 cm long liquid (basic hydrogen-peroxide, BHP) jets which is given by the position of chlorine injector below a jet injector (10 cm length was used mostly). A total high of the inner space of generator is 200 mm, inner volume ~ 480 cm^3. A BHP jet injector is made of alkamide plate with precisely drilled 304 holes of 0.8 mm in diameter and total surface of 1.528 cm^2 . BHP jets were driven by a force formed by the gear pump used for BHP loading into the upper part of generator (~1 atm). Their velocity was approximately 6 m s^{-1} at a BHP flow rate of ~ 55 l min^{-1}.

Close-loop BHP system

A close-loop flowing system with continuos BHP cooling was originally designed and constructed enabling a COIL operation up to ~ 5 minutes with 15 litres of BHP and at Cl_2 flow rate up to 40 mmol/s. Following from a linear grow of BHP temperature during generator operation, it can be presuppose that this generator can run ~4 minutes with 20 litres of BHP and at chlorine flow rate of 70 mmol/s until the BHP temperature increases from – 24 °C to – 4 °C. The close-loop system is formed by a heat exchanger with cooling power of ~2 kW in which ethanol as a coolant is cooled up to -30°C, and then, circulated through stainless steel coils in BHP tank, it removes heat from the BHP solution. It circulates between the BHP tank and jet SOG by means of a gear pump (Liquidflo's Equipment, model 312) with magnetic coupling and frequency transducer. Wetted parts of the pump are made of 316 stainless steel and HDPE, a pumping capacity is up to 100 l BHP min^{-1} (η=10-80 cP (ρ = 1.3 g/cm^3). A BHP temperature inside the generator is consequently controlled by this close-loop BHP flowing system and its capacity to remove a released reaction heat.

BHP tank (reservoir and mixing tank)

A BHP tank is made of high density polyethylene cylinder of 315/250 mm in diameter with a transparent Plexiglas bottom and cover. The jet SOG is fixed to the cover. Polyvinylidene fluoride (PVDF) pipe links a BHP drain from the tank into the inlet of generator. The tank is connected to the BHP pump. The pipe has a by-pass which is used when BHP is prepared in the same tank by mixing H_2O_2 with KOH. A cooling coils inside the tanks permit to mix approx. 2 litres BHP per minute. The mixing process is checked by temperature monitoring. To prevent a local BHP overheating, the liquid is slowly re-pumped through a by-pass pipe from the bottom to the top of mixing tank. The gear pump operates reliably without undesirable cavitations when BHP solution in the tank has volume at least 15 litres corresponding to a liquid height of 34 cm from bottom. A BHP of 5 -10 M [HO_2^-] is prepared from 65-70 % H_2O_2 and 42 % KOH.

Chlorine system

Chlorine is supplied from two pressurised gas bottles *via* a commercial controlled valves system and sent into the generator through a diaphragm flow meter with the analogue output. It enters the generator through two injectors placed in the side walls of generator body 10 (15) cm below the BHP injector. Chlorine injectors were made of stainless steel tubes of ∅10x1 mm with 23 holes of 1 mm in diameter drilled in each tube. A chlorine flow was diluted in some experiments with helium added downstream of generator.

Generator gas outlet and subsonic channel

In order to minimize a subsonic volume, the COIL device had no water condensation trap, so that water vapor content in the flow was controlled solely by a thermal management of the generator. A gas flow leaving the generator passes through a mechanical choke (throttle valve) at the generator exit and then elmg flat valve, the cross section of which was the same as the subsonic channel itself, i.e. 50 mm wide and 9.6 mm high. Straight behind the flat valve, a

diagnostic cell (duct) of the same cross section forms the next part of channel. It is equipped with ports that permit to measure chlorine absorption at 330 nm, O_2 (Δ_g) emission at 1270 nm by Ge photodiode, and $O_2(^1\Sigma_g)$ emission at 762 nm by Si photodiode for water concentration calculations. A gas temperature and pressure was also monitored in the cell. In some experimental tests, an injector of primary He was installed downstream of the diagnostic cell. It kept the same cross section as the channel and is formed by a stainless steel tube of 6 mm i.d. in the duct centre with two rows of 25 holes of 0.7 mm i.d. oriented under the angle of ± 45 ° to the gas flow axis.

Iodine injector (nozzle)

From the diagnostic cell, the gas flow enters iodine injectors. They were in a stainless steel block with inner duct of 50 x 9.6 mm and had two rows of holes (on the bottom and ceiling of the duct) aligned perpendicularly to the primary flow of oxygen. The first row had 21 holes of 0.8 mm in diameter, and the second row (4 mm downstream) had 42 holes of 0.4 mm. The I_2 injectors were resistively heated with two transistors up to 60 - 90°C. Beyond the iodine injection, the flow enters the sonic throat (expansion region). A distance between I_2 injection and the sonic throat plane was adjustable from 5 to 9 mm by a flat silicon rubber packing.

Supersonic nozzle and optical cavity

A supersonic nozzle made of stainless steel is inserted into a laser body made of Plexiglas. A single horizontal slit configuration was used. A nozzle throat had a cross-section of 3.35 cm^2 following from a critical height of 6.7 mm and width of 50 mm. A shape of the slit was designed according to calculations by the method of characteristics and is still opened by 3°. A critical gas velocity of 560 m/s was estimated for a gas mixture of O_2+He (1:4) (100 mmol Cl_2/s + 400 mmol He/s), a pressure in front of the throat of 6.6 kPa (50 torr) and Roots pump capacity 3000 m^3/hr. The expansion region accelerates the gas flow trough the lasing cavity to a supersonic flow (see chapter 3.2.). The expansion region was equipped with a Pitot tube for stagnation pressure measurement and a port in the wall for a static pressure measurement in the lasing cavity. A distance between the throat plane and optical axis of resonator was 5.5 mm (could be changed from 35 to 55 mm). The laser optical cavity (resonator) was 85 cm long and the lasing gain region occupies 5 cm. The nozzle ramps limited the multimode output beam size to 3.7 cm by 1.5 cm (see the beam patterns in Fig. 5). The resonator mirrors were isolated and protected from the main gas flow and BHP contamination by purging with He (~10 mmol/s). A maximum reflectivity mirror of 99.95% and an outcoupling mirror with reflectivities of 97.8 – 99.2% were used and made up the laser stable resonator. Both mirrors have 2.63 m radius of curvature and were 50 cm in diameter. The reflectivity of mirrors was measured by the Czech optical company (Meopta) where we bought them. A laser power measured only on the outcoupling mirror was recorded with the power meter LabMaster 213 Coherent with 100 W head (gauge). A resonator aligning and adjusting was made with He-Ne laser.

Vacuum pumping system

After leaving the optical cavity, the flow continues through a delta shaped diffuser connected with an efficient liquid nitrogen trap (condenser) to a Roots blower and a single-stage rotary pump (RUTA 3001/2, Leybold). The stand has a nominal pumping capacity of 3000 $m^3 h^{-1}$. The LN_2 trap has a built-in ribbed heat exchanger made of copper.

Iodine system

Iodine is kept in solid form inside an originally designed I_2 tank, from which the iodine vapor is picked up and carried out of the vessel with pre-heated helium flowing through the I_2 bed. The I_2 tank is made of stainless steel cylinder with a glass liner, and, is equipped with a heater of He placed at the bottom of tank. In the heater, He flow can be heated up to 400°C. The I_2 tank has capacity for ~30 min operation at I_2 flow rate up to 1.7 mmol/s. Iodine flow rate was calculated by measuring iodine absorption at 480 nm in a diagnostic cell with the optical length of 8.3 cm placed downstream of the tank exit. The absorption extinction coefficient ε_{480} = 326 litre/mol cm (or cross section $\sigma_{480} = 1.77 \times 10^{-18}$ cm^2) was used. The diagnostic duct was equipped with pressure and temperature sensing and fibre optics. The calculated I_2 flow rate was then used to control the amount of secondary helium sent into I_2 tank. Additional He diluent was added after the iodine tank though by-pass to ensure that iodine leaving the injectors penetrates enough into the primary flow.

Data acquisition system

An analogue/digital converter with 32 channels for data acquisition and their processing by PC was originally designed and constructed. A specially modified software Scopewin was used. The following parameters were recorded so far: 1 - jet temperature, 2 - BPP tank temperature, 3 - gas temperature in diagnostic cell, 4 - gas temperature in iodine cell, 5 - iodine tank temperature, 6 - iodine injector temperature, 8 - generator pressure, 9 - BHP tank pressure, 10 - pressure in diagnostic cell (subsonic channel), 11 - iodine cell pressure, 12 - laser cavity pressure, 13 - Pitot tube pressure, 14 - $O_2(^1\Delta_g)$ detection, 15 - $O_2(^1\Sigma_g)$ detection, 16 - residual chlorine detection, 17 - iodine detection, , 18 - chlorine flow rate, 19 - chlorine pressure, 20 - He_{prim} flow rate, 21 - He_{prim} pressure, 22 - He_{sec} flow rate, 23 - He_{sec} pressure, 24 - laser power.

3. Test of operation of COIL subsystems and complete device as a laser. Summary of experimental results

- The closed-loop BHP system was tested. An optimum frequency of the gear pump speed adjusted to parameters of BHP jet injector in generator and optimum opening of throttle valve at the generator exit was found.
- Output characteristics of jet SOG, i.e. $O_2(^1\Delta_g)$ yield, Cl_2 utilization and water vapor concentration were examined, and following from these results, a jet SOG operation was optimized.

- Gas dynamics conditions in the subsonic channel and the supersonic region were investigated, resulting in the estimation of Mach numbers.
- An iodine vapour production by preheated helium flowing through the I_2 tank with solid I_2 was investigated, and mixing of primary flow ($O_2(^1\Delta_g)$ + He) with secondary flow (He + I_2) was tested.
- A complete device as a laser has been investigated. From the performed sets of experiments, laser parameters as the laser power, small signal gain, saturation intensity, and chemical efficiency could be were evaluated.

Some preliminary and partial results of our investigation were included in the Interim Reports 0001 and 0002 of this contract. Recent results are summarised below.

3.1. Test of jet singlet oxygen generator

3.1.1. Experimental conditions for effective and reliable operation of jet SOG (with suppressed entraining of BHP droplets and BHP foam into gas channel) were investigated at various flow rates of Cl_2, He_{prim}, and He_{sec}, and opening of the throttle (choke) valve at the generator exit. The generator characteristics were measured in the range of Cl_2 flow rate of 20-60 mmol/s, and with primary helium introduced either downstream of the generator exit (into the channel) or admixed into chlorine flow upstream of the generator. The upper flow rate of chlorine was limited by technical and safety conditions until an adjusted chlorine management is installed. It is arranged now.

a/ Typical values of generator pressure, P_{gen}, and singlet oxygen yield, Y_Δ, determined from $O_2(^1\Delta_g)$ detection in diagnostic cell, are shown in Table 1 and Figs. 1a – 1c. These values were obtained in experiments when **He_{prim} was introduced downstream of the generator** with the flow rate of 80 mmol/s.

Tab. 1

n_{Cl2}, mmol/s	P_{gen}, kPa (torr)	Y_Δ, %
40	4.6 (34.6)	59
40	4.1 (30.8)	64
50	4.7 (35.8)	60
50	4.6 (34.6)	64
60	4.9 (36.8)	62

The pressure in subsonic channel was in the range of 3.2 - 3.9 kPa (24.1 – 29.3 torr) (see Fig. 1a). The yield was practically the same for all Cl_2 flow rates investigated (see Fig. 1b). The gas temperature in subsonic channel was rather high and exceeded 60°C at 60 mmol Cl_2 /s (see Fig.1c), It was still increasing during injection of secondary flow (I_2 + He_{sec}) into the primary flow. An effect of speeding up the pooling reaction of $O_2(^1\Delta_g)$ at relatively high pressure caused by He_{prim} introduction into channel is obvious.

b/ Under conditions when **He_{prim} (80 mmol/s) was admixed into Cl_2 flow upstream of the generator,** the pressure in subsonic channel remained around 2.8 kPa (21 torr) at all throttle valve positions (see Fig. 2a), and the gas temperature in channel is decreased due to He_{prim} cooling by BHP jets (compare Figs.1c and 2c). The pooling reaction is slowed down, resulting in increasing in the $O_2(^1\Delta_g)$ yield (compare Figs. 1b and 2b). Typical values of pressure in generator, P_{Gen}, and yields, Y_Δ, at 40 mmol Cl_2/s but different opening of throttle valve et generator exit are shown in Table 2.

Tab. 2

TV position*	5	6	8	9
P_{gen}, kPa (torr)	5.8 (43.6)	4.4 (33.1)	3.9 (29.3)	3.7 (27.8)
Y_Δ, %	77	78	84	89

*see caption to Fig. 1a

3.1.2. The effect of jet SOG run time on the BHP jets temperature, T_{jets}, and water vapour partial pressure, P_{H2O}, was further investigated. A typical example of results measured at 40 mmol Cl_2 /s and 80 mmol He_{prim}/s admixed into Cl_2 flow is shown in Fig. 2d. During 1 minute run, the temperature of BHP jets increased from -13 to -11°C, and P_{H2O} from 65 Pa to 105 Pa in average. The ratio of P_{H2O} / P_Δ was then increased from 8% to 14%. The water partial pressure was evaluated from data taken in the diagnostic cell (subsonic channel). The temperature of BHP jets was measured at the bottom of generator during the chlorinating, and it was by 2 – 4°C highe due to the exothermic reaction than the BHP temperature in tank (Fig. 3).
A chlorine utilization in the jet SOG was very high - from 0.93 to 0.98.

3.2. Test of gas dynamic conditions in COIL device

The estimation of gas dynamic conditions in subsonic channel and supersonic region of COIL device was carried out during a „cold flow run", when no iodine was injected into the primary flow and gaseous nitrogen was used instead of chlorine. During these experiments, pressure was monitored at four places of the device: in generator, P_{gen}, in subsonic channel (diagnostic cell), P_{chann}, in supersonic lasing region with a side wall tube, P_{las} (the static pressure), and in centreline of the laser cavity with a Pitot tube, P_{Pitot}.

The average Mach number, M_1, in the subsonic channel was evaluated from the equation[1]

$$n = (\kappa / R\,\mu)^{1/2}\,(A\,P_{stat} / T^{*1/2})\,M\,\{1 + M^2(\kappa - 1)/2\}^{1/2} \qquad (1)$$

where n is the total molar flow rate, κ is the adiabatic constant of gas mixture, R is the gas constant, μ is the molecular weight, A is the flow cross section, P_{stat} is the static pressure, T^* is the stagnation temperature.

For the experimental conditions, $n_{N2} = 22.3$ mmol/s
$n_{He} = 89.5$ mmol/s
$n_{mix} = 0.1118$ mol/s
$\kappa_{N2} = 1.401$
$\kappa_{He} = 1.630$
$\kappa_{mix} = \sum n_i \kappa_i / \sum n_i = 1.584$
$P_{channel} = 2055$ Pa
$\mu = \sum n_i \mu_i / \sum n_i = 8.79\ 10^{-3}$ kg/mol
$A = 4.75\ 10^{-4}\ m^2$ (the cross section of channel 9,5 x 50 mm)
$T^* = 293$ K
$R = 8.314$ J/grad mole

the average Mach number in the subsonic channel is $\mathbf{M_1 = 0.41}$.

The average Mach number in the supersonic region, M_2, (in the optical axis of resonator) was calculated by eq. (1), for the experimental conditions given in Tab. 3.

Tab. 3

n_{N2}, mmol/s	n_{He}, mmol/s	n_{mix}, mmol/s	P_2, Pa	μ, kg/mol	He:N_2	κ	**M_2**
20.5	91.4	111.9	174	8.374	4.5	1.571	**1.94**
43.5	179.6	223.1	158	8.686	4.13	1.567	**1.73**
60.5	288	344.7	380	7.942	4.8	1.576	**1.42**

The local Mach number, M_2, in the supersonic region was calculated by the relation[2]

$$P_{stat} / P_{pit} = \{2 / [(\kappa - 1) M_2^2]\}^{\kappa/(\kappa-1)} \{[2 M_2^2 \kappa /(\kappa + 1)] - [(\kappa - 1)/(\kappa + 1)]\}^{1/(\kappa-1)} \quad (2)$$

where P_{pit} is the Pitot tube pressure.

In Tab. 4 are given calculated values of M_2 together with the experimental conditions, and for the cross section $A = 9.16\ 10^{-4}\ m^2$ at a distance of 53 mm from the throat plane where h = 16 mm and w = 55 mm.

Tab. 4

n_{N2}, mmol/s	n_{He}, mmol/s	He:N_2	κ	P_{stat}, Pa	P_{Pit}, Pa	**M_2**
22.3	89.5	4.0	1.564	174	1457	**2.37**
20.5	91.4	4.5	1.571	158	1349	**2.40**
43.5	179.6	4.1	1.567	380	3024	**2.31**
60.5	288	4.8	1.576	741	5139	**2.14**

3.3. Test of iodine management

3.3.1. Test of newly fabricated iodine vaporizer

Iodine vapor generation in originally designed and fabricated iodine tank (vaporizer) was investigated. A required I_2 flow rate for lasing is controlled by temperature of helium flowing through the tank with solid iodine bed, He flow rate, and duration of additional outer preheating of tank. An optimum voltage on the heater heating helium He up to 400°C, and supply conditions for heating bands were examined. It was found that a response of iodine flow rate on the change of He flow rate was nearly immediate (less than 1 minute), a response on the jump of electric power supplying the heater was within a few minutes, and a response on the jump of electric power supplying bands required tens of minutes. The bands were therefore switch on approximately one hour before a start of experimental run. A resistively heated iodine injectors up to 60-90°C needed approximately half and hour before a run.

3.3.2. Test of mixing of primary (O_2 + He) and secondary (I_2 + He) flow

Iodine mixing conditions were investigated and yellow flame from I_2 pre-dissociation state was observed through a transparent laser body and transparent slit nozzle, and recorded with video camera. The gas parameters and hardware design parameters were included into the estimation of injection and mixing of transverse secondary gas jet into a subsonic primary gas flow. A hardware design parameters were used to estimate full penetration conditions as the **full penetration parameter**, Π_{full}, according to the relation[3]

$$\Pi_{full} = d\, A_s / 5\, D\, A_p \qquad (3)$$

where d is the height of subsonic channel, D is the diameter of iodine injector holes, A_s is the cross-section of holes for secondary flow, A_p is the cross-section of channel for primary flow.

For our hardware design parameters, $d = 9.5$ mm,
$D_1 = 0.8$ mm, $D_2 = 0.4$ mm,
$A_s = 2 \times \{21 \times \pi(0.8^2/4) + 41 \times \pi(0.4^2/4)\}\mathrm{mm}^2$,
$A_p = 50 \times 9.5\ \mathrm{mm}^2$,

The average Π_{full}, evaluated as $(\Pi_{full\text{-}1} + \Pi_{full\text{-}2}) / 2$, where $\Pi_{full\text{-}1}$ is calculated for D_1 and $\Pi_{full\text{-}2}$ for D_2, is

$$\mathbf{\Pi_{full} = 0.197}$$

The iodine jet penetration was estimated by calculation of penetration parameter defined by flow conditions of primary and secondary flow according to the relation[3]

$$\Pi = n_s / n_p\, \{(M_s\, T_s\, P_p / M_p\, T_p\, P_s)\}^{1/2} \qquad (4)$$

where n_s and n_p is the molar flow rate of secondary and primary flow, respectively, M_s and M_p is average molecular weight of primary and secondary gas mixture, T_s, T_p is temperature, P_p and P_s is pressure of primary and secondary flow, respectively.

For our experimental conditions, where $I_2/O_2 \sim 0.0175$ at $P_{out} = 280$ W,

primary flow: 40 mmol O_2 /s + 80 mmol He /s
$n_p = 120$ mmol /s
$M_p = 13{,}33 \times 10^{-3}$ kg / mol
$T_p = 305$ K
$P_p = 2600$ Pa

secondary flow: 40 mmol He / s + 0.7 mmol I_2 /s
$n_s = 40{,}7$
$M_s = 4.74 \times 10^{-3}$ kg / mol
$T_s = 353$ K
$P_s = 4400$ Pa

the penetration factor was $\Pi = \mathbf{0.166}$

3.4. Test of completed device as a laser

3.4.1. Experiments with laser generation

Sets of experiments were carried out to generate a laser power. During these COIL runs, an optimum ratio of I_2/O_2 was searched for given experimental conditions. For the beginning, the Cl_2 flow of 40 mmol/s, He_{prim} of 80 mmol/s, and He_{sec} of 40 mmol /s were kept constant, and the following parameters were changed:
a/ the introduction of primary He either downstream of generator or admixed into chlorine upstream of generator,
b/ the I_2 flow rate in the range of 0.2 - 2.0 mmol/s,
c/ the distances between I_2 injection and nozzle throat plane, l_i, which was either 9 mm or 5 mm in average,
d/ resonator mirrors with various total output coupling (0.95 - 2.0 %).

The output power from 60 W to 150 W was measured with $l_j =$ 9 mm, I_2 flow rate of 0.5 - 1.25 mmol/s and total output coupling of 0.95 - 2.0 %. When the primary He was added into Cl_2 flow upstream of the generator, a laser operation was more stable.

The laser power increased up to nearly 300 W (280 W in average) when a distance between I_2 injection and nozzle throat plane was shortened to 5 mm. Other conditions remained the same. The maximum reflectivity mirror used had the transmission of 0.005%, and the outcoupling mirror 1.9%. The ratio of I_2/O_2 was 0.0175 (see Fig. 4). Multimode beam patterns on wood obtained during several seconds in this experiment are shown in photos (Fig. 5).

The **laser power of ~300 W** was the highest power achieved on our COIL device under the above conditions. They were not evidently optimum yet, as follows from a low evaluated **chemical efficiency of 0.083.**

3.4.2. Evaluation of small signal gain

An indirectly measured small signal gain was evaluated from data on the intensity saturation that were taken by changing the reflectivity of total outcoupling and

measuring the laser power. From results of the above described experiments, a dependence of P_{out} on I_2 flow rate for three total values of outcoupling was plotted. It is shown in Fig. 6. The Rigrod gain saturation model[4] was then used to calculate the small signal gain, α_{34}, and the saturation intensity, I_s, from the dependence of laser power *vs.* the total outcoupling, δ_e, for every value of n_{I2} by[4]

$$P_w = s\,\delta_e\,\{[\,2\,\alpha_{34}\,l_g\,/\,(\delta_e + \delta_o)]^2 - 1\}\,I_s \qquad (5)$$

where *s* is the output beam cross-section, the factor δ_e represents the total external coupling given by the definition[5] $\delta_e \equiv \delta_1 + \delta_2$. For a weakly coupled COIL laser cavity, the mirror transmission T_1 is equal to $1 - R_1 \approx \delta_1$ (R_1 is the reflectivity of the output mirror), and T_2 is equal to $1 - R_2 \approx \delta_2$ (R_2 is the maximum reflectivity mirror), provided that both δ_1 and δ_2 are reasonably small compared to unity[5]. The factor δ_o represents all internal cavity losses. Further, α_{34} is a small signal gain for the 3-4 transition of the hyperfine structure of the atomic iodine transition $^2P_{1/2} \rightarrow {}^2P_{3/2}$, l_g is the gain length, and I_s is the saturation intensity.

Following from our lasing condition, where $s = 5.5$ cm^2, $l_g = 5$ cm, $\delta_1 = 0.0190$ and $\delta_2 = 0.0005$, and $\delta_o = 0.09$ (for the best fitting to the experimental results), the values of saturation intensity and small signal gain were calculated. They are presented in Tab. 5. The quantity η_r in Tab. 5 represents a resonator (power) extraction efficiency, or otherwise, the normalized output intensity of laser. It can be expressed as[5]

$$\eta_r \equiv I_{out}\,/\,I_{avail} \qquad (6)$$

and using eq. (5), it was calculated by the relation

$$\begin{aligned}\eta_r &= (P_{out}\,/\,s)\,/\,(2\,\alpha_{34}\,l_g\,I_s)\\ &= \delta_e\,[\{2\,\alpha_{34}\,l_g\,/\,(\delta_o + \delta_e)^2\} - \{1\,/\,(2\,\alpha_{34}\,l_g)\}] \qquad (7)\end{aligned}$$

Tab. 5.

n_{I2}, mmol s^{-1}	α_{34}, cm^{-1}	I_s, W cm^2	η_r, %
0.5	1.23 x 10^{-2}	7093	4.15
0.75	1.27 x 10^{-2}	6502	5.3
1.0	1.29 x 10^{-2}	5838	5.86
1.25	1.30 x 10^{-2}	5273	6.14
1.5	1.29 x 10^{-2}	5411	5.86
1.75	1.28 x 10^{-2}	4721	5.58

3.5. Comparison of laser parameters and characteristics of COIL devices

The first attempt to compare laser parameters and characteristics of the COIL device in the Institute of Physics (jetSOG-COIL) with VertiCOIL device (diskSOG-COIL) investigated in the USAF Research Laboratory is presented in Tab. 6. The data on VertiCOIL were taken from the Tab.1 *Long run time test* # 1 in the paper by Phipps *et al*[6] and Tab. 2 *Required inputs to COIL saturation model* in the paper by Helms *et al*[7].

Tab. 6

	VertiCOIL in AFRL	**JetSOG-COIL in IP**
Total average power	420 W	280
Run time	13 minutes	1,5 min
Chlorine flowrate	36 mmol/s	40 mmole/s
Primary He diluent	135 mmol/s	80 mmol/s
Generator pressure	38 torr	44 Torr
Chlorine utilization	0.98	0.99
Diagnostic duct pressure	28 torr	26.3 torr
Laser cavity pressure	4.5 torr	2.2 torr
BHP inlet temperature	-30°C	-25°C
BHP outlet temperature	-19°C	-18°C
Diagnostic duct temperature	-10°C	+4°C
Penetration factor, Π	0.11	0.166
Full penetration factor, Π_{full}	-	0.197
Chemical efficiency	0.12	0.08
I_2/O_2	0.017	0.0175
Starting BHP molarity	7.2 O_2H^-/0.5 H_2O_2	8M[H_2O_2]/6M[KOH]
$O_2(^1\Delta_g)$ yield	0.54 (assumed)	0.89
Mirror reflectivities	0.997/0.982	0.9995/0.981
Mirror scattering loss	0.0025/0025	not estimated
Mirror absorption loss	$10^{-5}/10^{-5}$	not estimated
Mode length	3.2 cm	3.7 cm
Gas velocity in cavity	$1x10^5$ cm/s	~$5,6x10^4$ cm/s
Small signal gain	0.014 cm^{-1}	0.0127 cm^{-1}
Saturation intensity	-	6.5 kW cm^{-2}

4. Conclusion

We started with the experiments on a complete device test as a laser seven month ago approximately. The few first laser experiments called for some technical modifications of device that slowed down the work on lasing. In spite of that, we succeed to operate the COIL with a reasonable laser output power under conditions which permit us to evaluate the small

signal gain, the saturation intensity and resonator extraction efficiency. Although the achieved parameters and characteristics are not optimum yet, we gathered valuable experiences on the supersonic-type COIL for follow-on experimental work to optimize them in a near future.

During the next testing the COIL device, the output power will be measured at various Cl_2 flow rate up to 70 mmol/s with optimum I_2/O_2 ratio. A great attention will be further paid to the optics of resonator. New mirrors of higher radius of curvature (5 m) or flat, and mirrors of better quality are plane to be used.

A direct measurements of the small signal gain and laser cavity temperature with a diode probe diagnostics, which are also planned, will gather results which permit a more serious comparison of laser characteristics of our COIL device with VertiCOIL.

5. Acknowledgement

We are very grateful for the support of this work by the USAF European Office of Aerospace Research and Development (EOARD), and we thank very much to Prof. Martin Stickley, the Chief of Lasers, Optics and Materials, at EOARD for his assistance with this contract. We benefit very much during the work on the contract from discussions with Dr. Gordon Hager, Dr. Harro Ackermann, Dr. Keith Truesdell, Dr. Charles Helms and Dr. Kip Kendrick from the USAF Research Laboratory/DE at Kirtland Base.

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5/ A.E. Siegman, *Lasers*, pp. 473-485, 1986

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7/ C.A. Helms, T.L. Rittenhous, S.P. Phipps, K.A. Truesdell, G.D. Hager, „*Extraction efficiency of a 5-cm gain length supersonic chemical oxygen-iodine laser*“, Proc. SPIE **3092,** p. 544, 1996.

Caption to figures

Fig. 1a – 1c. He_{prim} of 80 mmol/s was introduced downstream of the generator.

Fig. 1a. Time course of pressure in generator and subsonic channel (diagnostic cell), and $O_2(^1\Delta_g)$ partial pressure measured at 40 – 60 mmol Cl_2/s and different opening of throttle (choke) valve (TV) at generator exit. TV5 represents a position of the flap valve containing with the gas glow direction the angle (90-50)°, TV6 ~ 30°, TV7 ~ 20° and TV9 ~ 0°.

Fig. 1b. Time course of $O_2(^1\Delta_g)$ yield at 40 – 60 mmol Cl_2 /s and different opening of throttle valve (TV) (see the caption of Fig. 1a).

Fig. 1c. Time course of temperature in subsonic channel at 40-60 mmol Cl_2 /s and different opening of throttle valve TV (see the caption of Fig. 1a).

Fig. 2a – 2c. He_{prim} of 80 mmol/s was introduced upstream of the generator, admixed into Cl_2 flow.

Fig. 2a. Time course of pressure in generator, subsonic channel, laser cavity and $O_2(^1\Delta_g)$ partial pressure at different opening of the throttle valve (TV) (see the caption of Fig. 1a). The Cl_2 flow rate of 40 mmol Cl_2/s and He_{prim} of 80 mmol /s was kept constant.

Fig. 2b. Time course of $O_2(^1\Delta_g)$ yield at different positions of throttle valve (TV) (40 mmol Cl_2 /s)

Fig. 2c. Time course of temperature in subsonic channel at different positions of throttle valve (TV) and 40 mmol Cl_2 /s.

Fig. 2d. Time course of BHP jets temperature and water vapor partial pressure. Experimental conditions are given in the caption of Fig. 2a.

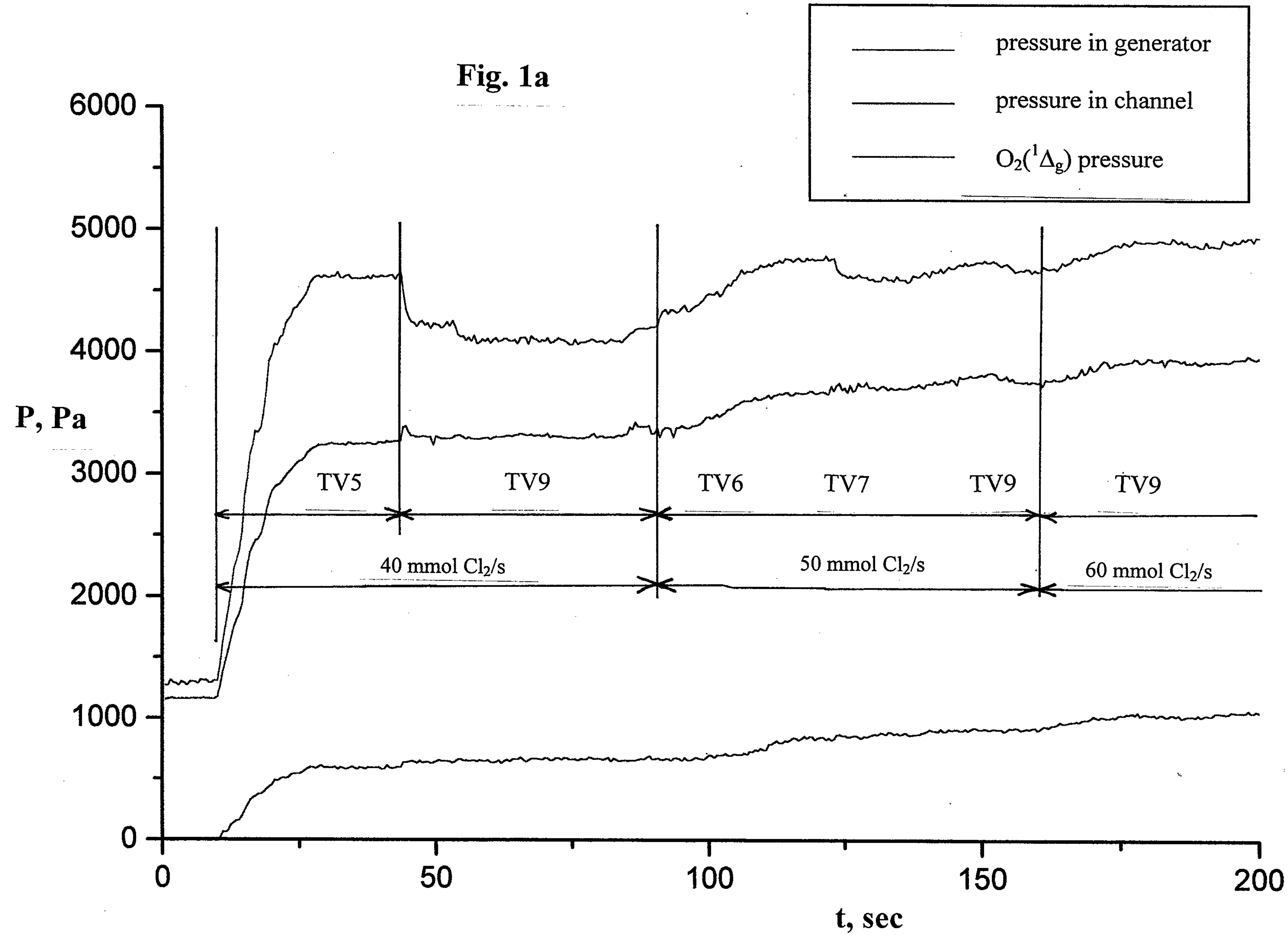
Fig. 3. Temperature change of BHP jets and BHP solution in tank during experimental run (34 mmol Cl_2/s).

Fig. 4. A course of I_2 molar flow rate and laser power, P_w, during one experimental run at 40 mmol Cl_2 /s, 80 mmol He_{prim} /s, and 40 mmol He_{sec} /s.

Fig. 5. Photos of beam patterns obtained during several seconds on wood with laser power of 280 W.

Fig. 6. Plot of laser power, P_w, *vs.* I_2 molar flow rate at 40 mmol Cl_2 /s, 80 mmol He_{prim} /s, 40 mmol He_{sec} /s, and three values of total output coupling.

Fig. 1a



pressure in generator
pressure in channel
$O_2(^1\Delta_g)$ pressure
P, Pa
6000
5000
4000
3000
2000
1000
0
TV5
TV9
TV6
TV7
TV9
TV9
40 mmol Cl_2/s
50 mmol Cl_2/s
60 mmol Cl_2/s
0
50
100
150
200
t, sec

Fig. 1b

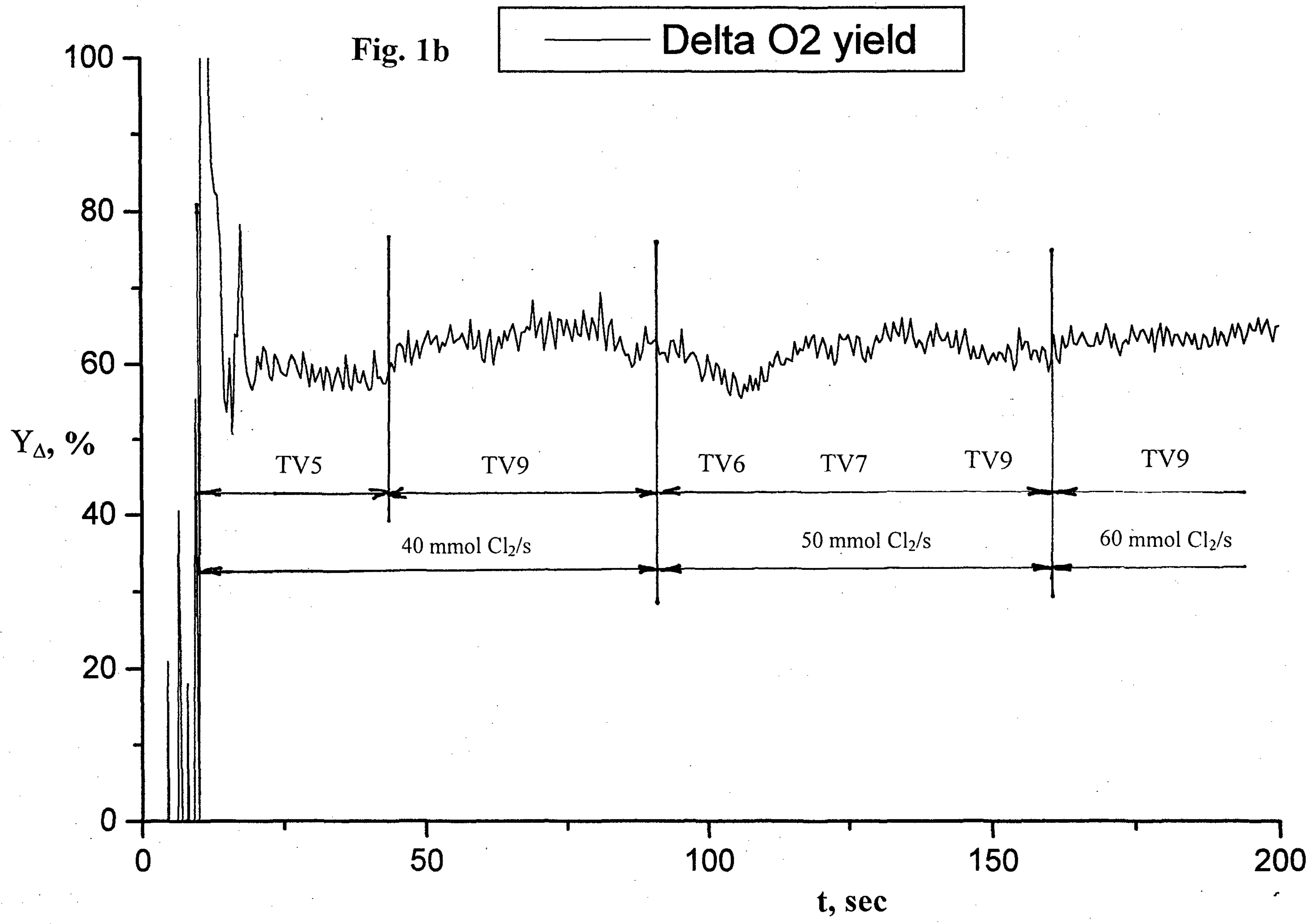
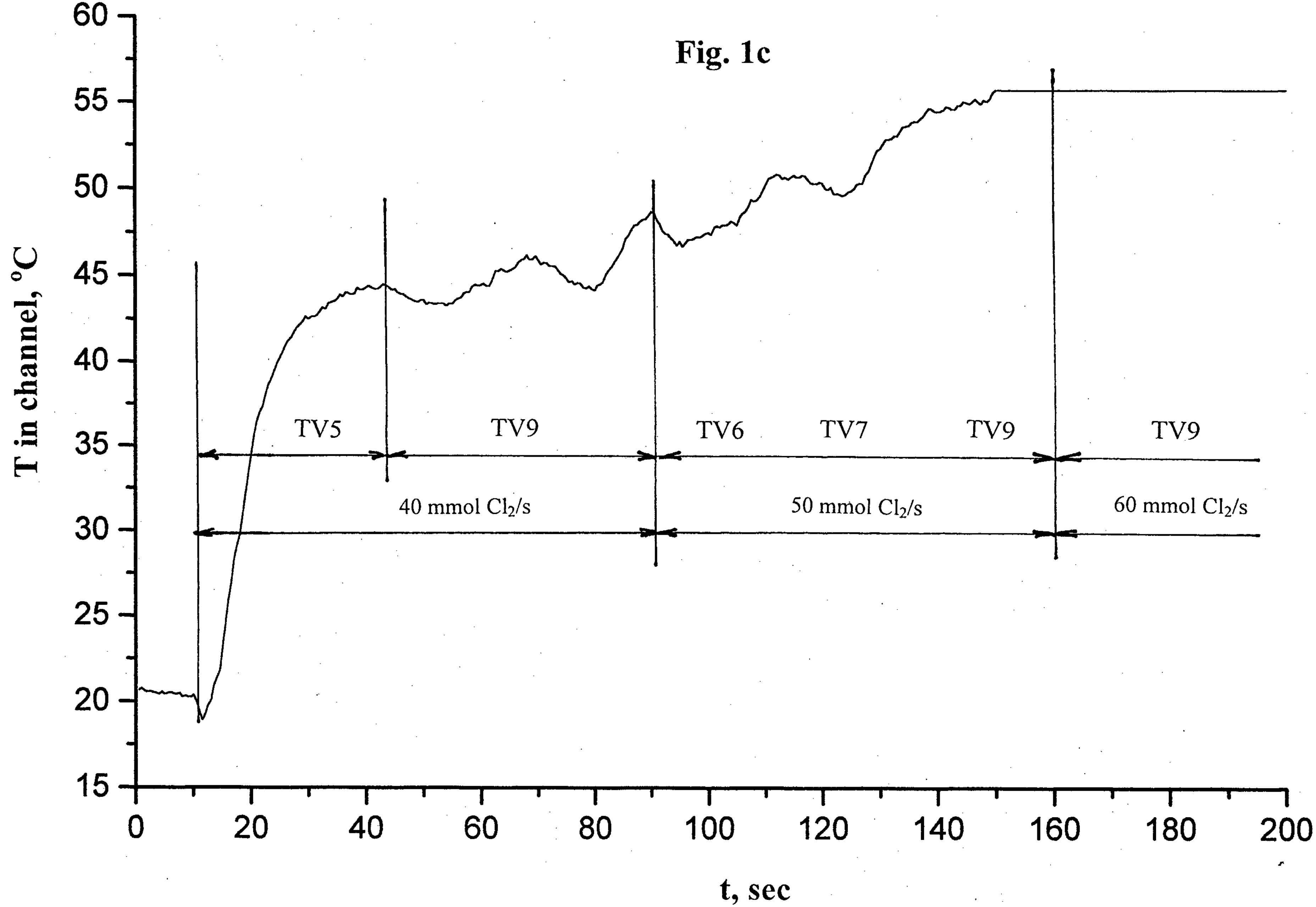
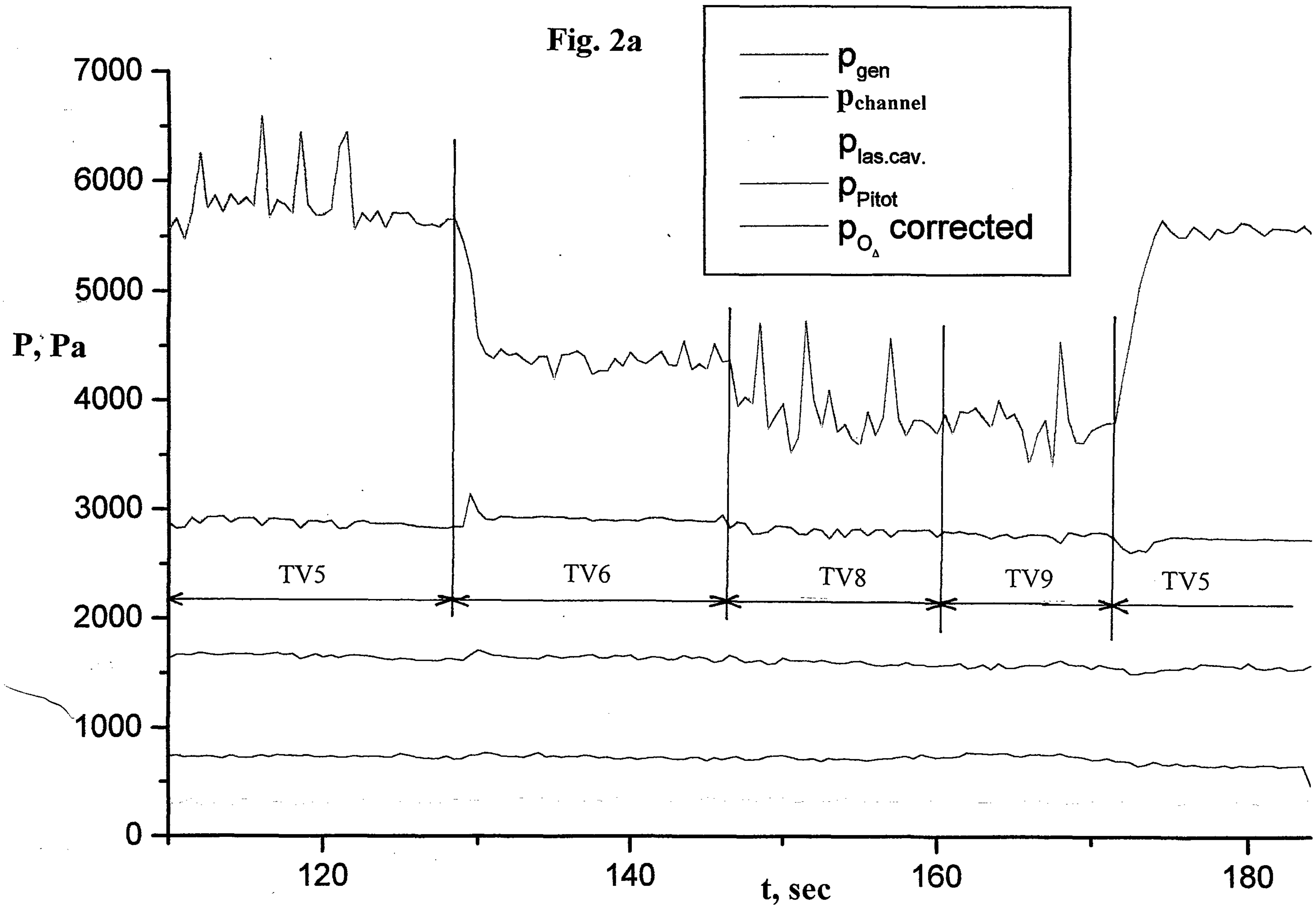

Delta O2 yield
Y_Δ, %
100
80
60
40
20
0
0
50
100
150
200
t, sec
TV5
TV9
TV6
TV7
TV9
TV9
40 mmol Cl_2/s
50 mmol Cl_2/s
60 mmol Cl_2/s

Fig. 1c



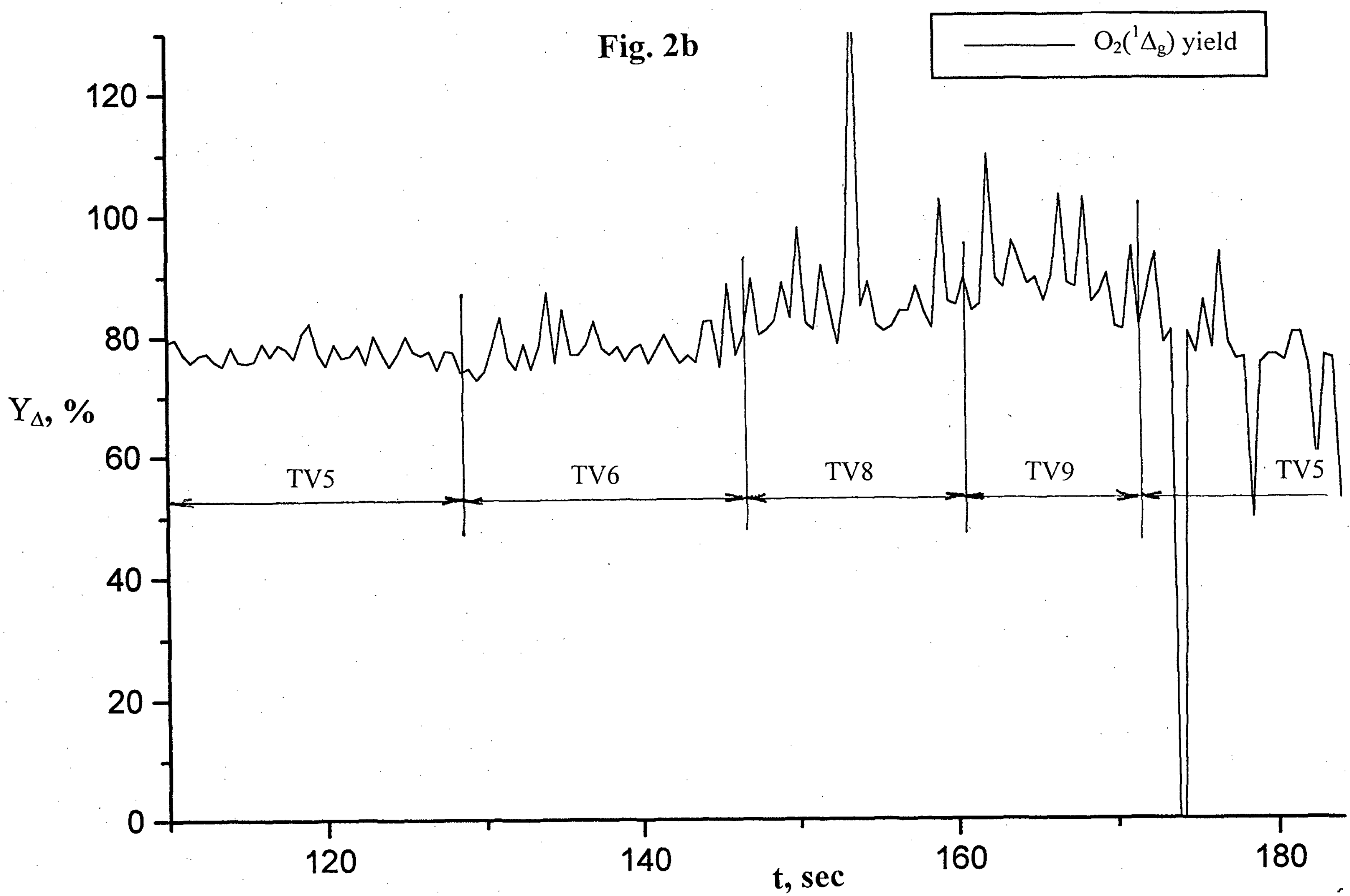
T in channel, °C
t, sec
TV5
TV9
TV6
TV7
TV9
TV9
40 mmol Cl2/s
50 mmol Cl2/s
60 mmol Cl2/s
60
55
50
45
40
35
30
25
20
15
0
20
40
60
80
100
120
140
160
180
200

Fig. 2a



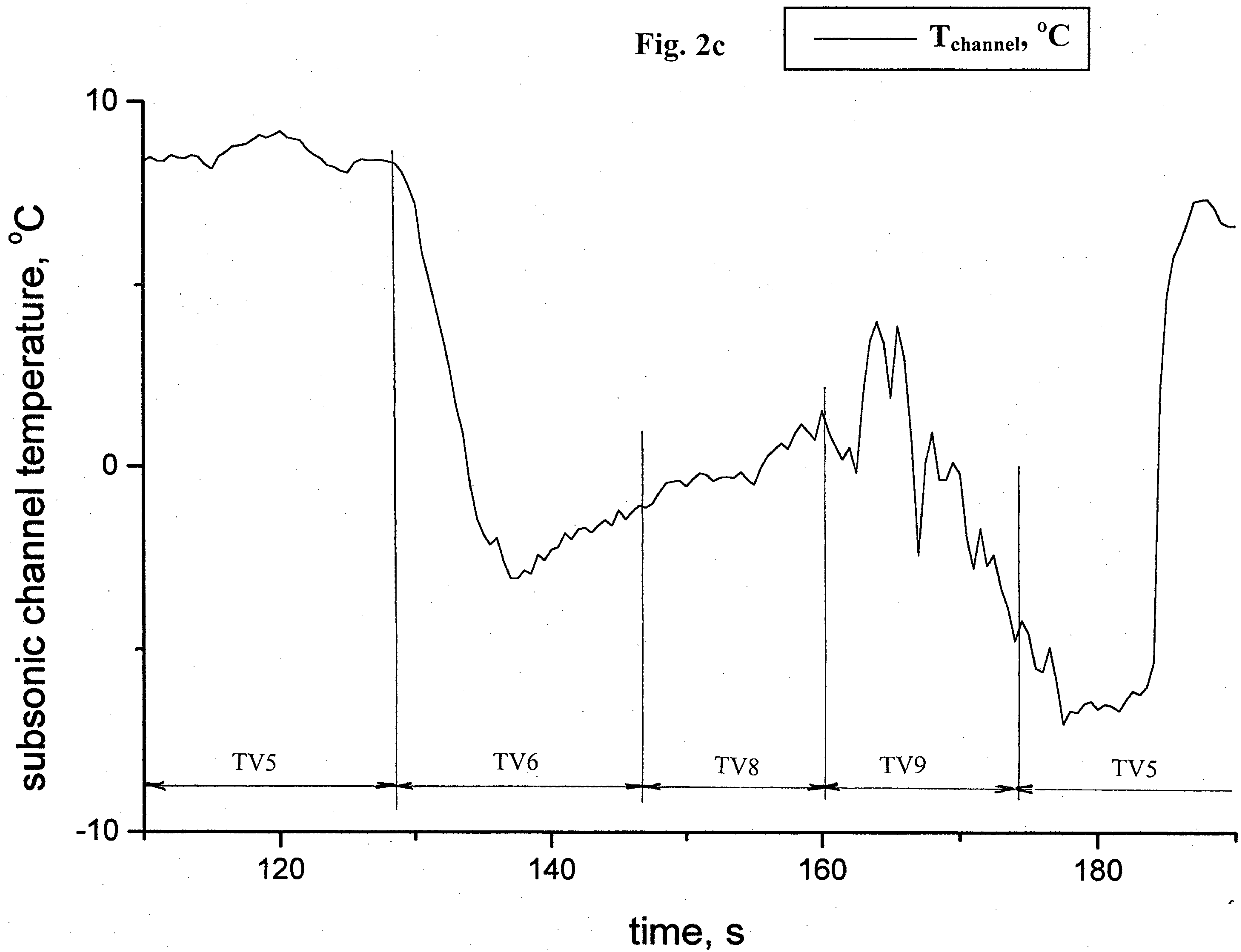
p_gen
p_channel
p_las.cav.
p_Pitot
p_O_Δ corrected
7000
6000
5000
4000
3000
2000
1000
0
P, Pa
TV5
TV6
TV8
TV9
TV5
120
140
160
180
t, sec

Fig. 2b



$O_2(^1\Delta_g)$ yield
120
100
80
60
40
20
0
Y_Δ, %
TV5
TV6
TV8
TV9
TV5
120
140
160
180
t, sec

Fig. 2c



$T_{channel}$, °C
10
0
-10
subsonic channel temperature, °C
TV5
TV6
TV8
TV9
TV5
120
140
160
180
time, s

Fig. 2d

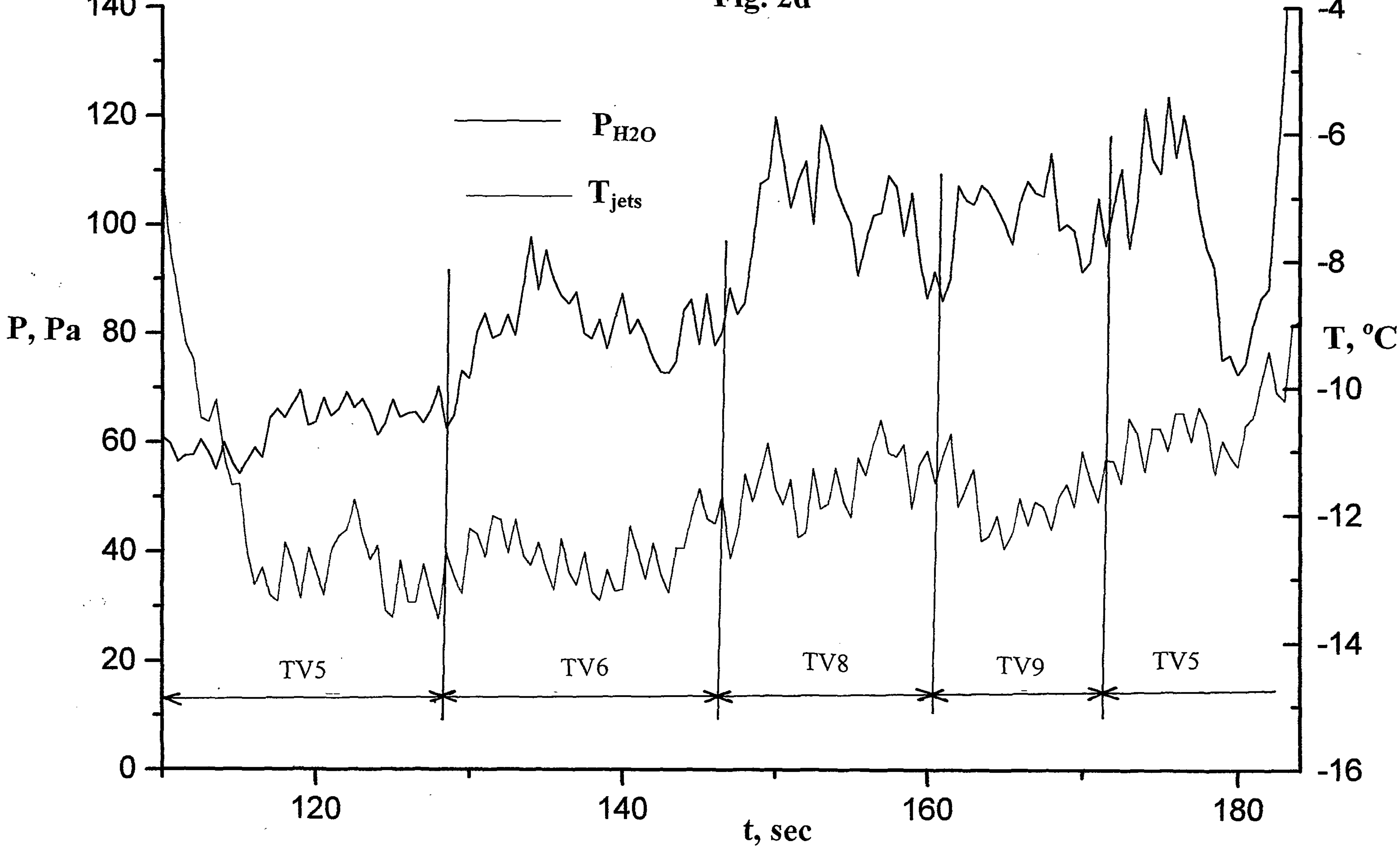

P, Pa
140
120
100
80
60
40
20
0
T, °C
-4
-6
-8
-10
-12
-14
-16
t, sec
120
140
160
180
P_H2O
T_jets
TV5
TV6
TV8
TV9
TV5

Fig. 3

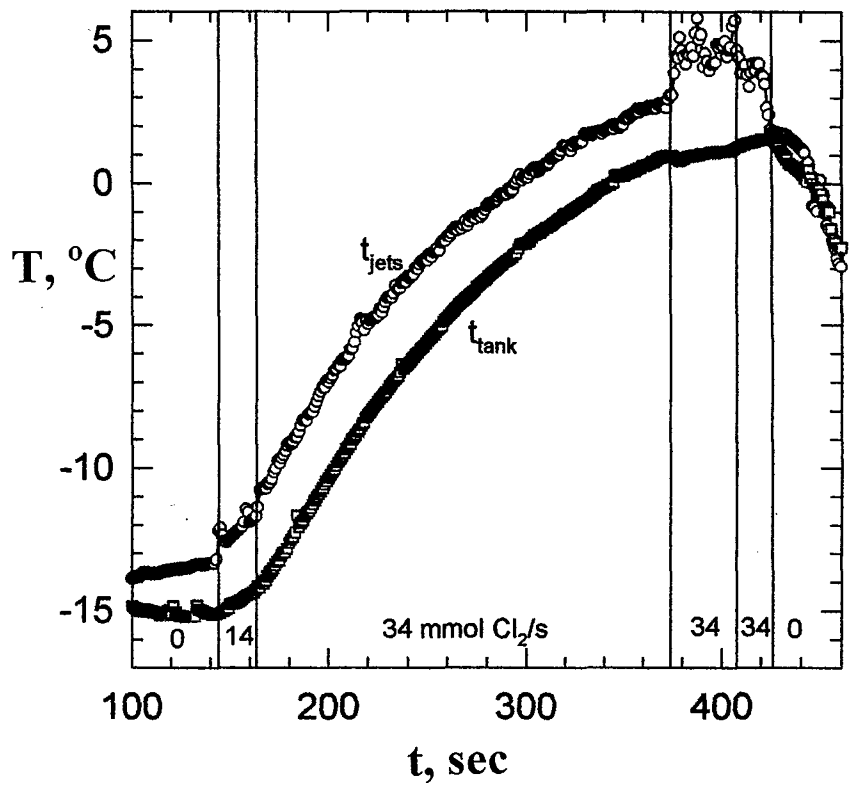
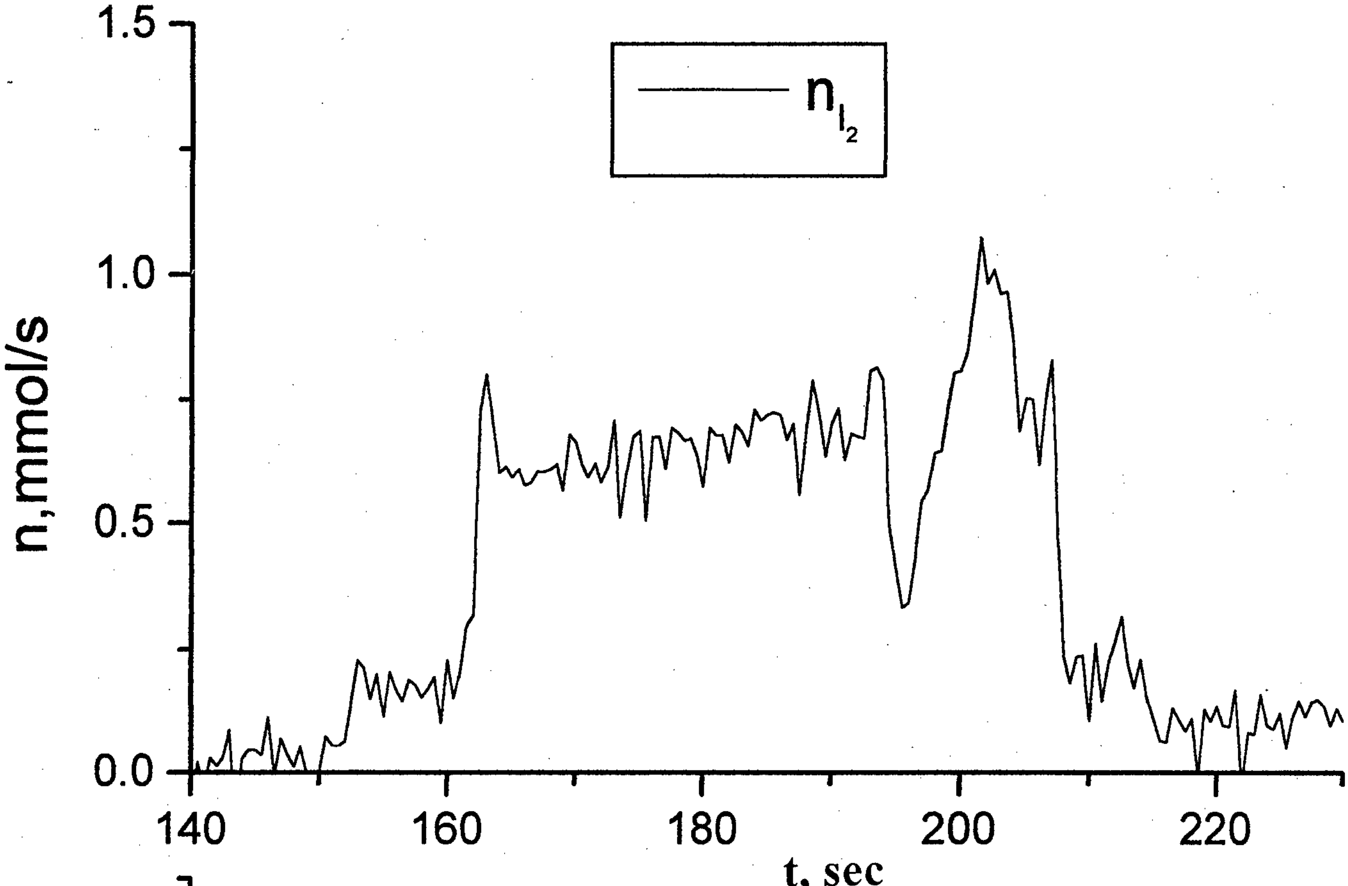
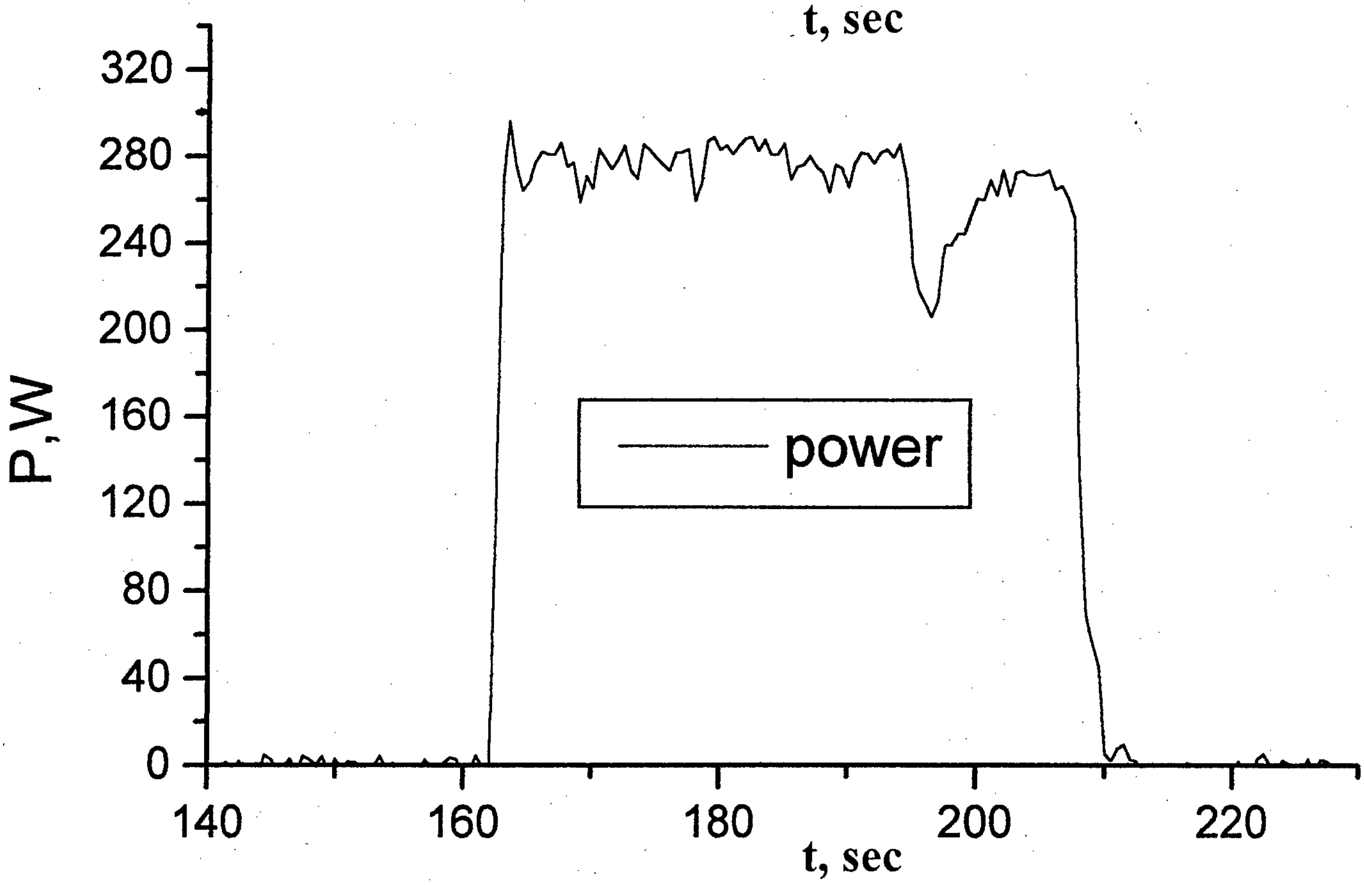

T, °C
5
0
-5
-10
-15
100
200
300
400
t, sec
t_jets
t_tank
0
14
34 mmol Cl2/s
34
34
0

Fig. 4


1.5
1.0
0.5
0.0
n,mmol/s
n_{I_2}
140
160
180
200
220
t, sec


320
280
240
200
160
120
80
40
0
P,W
power
140
160
180
200
220
t, sec

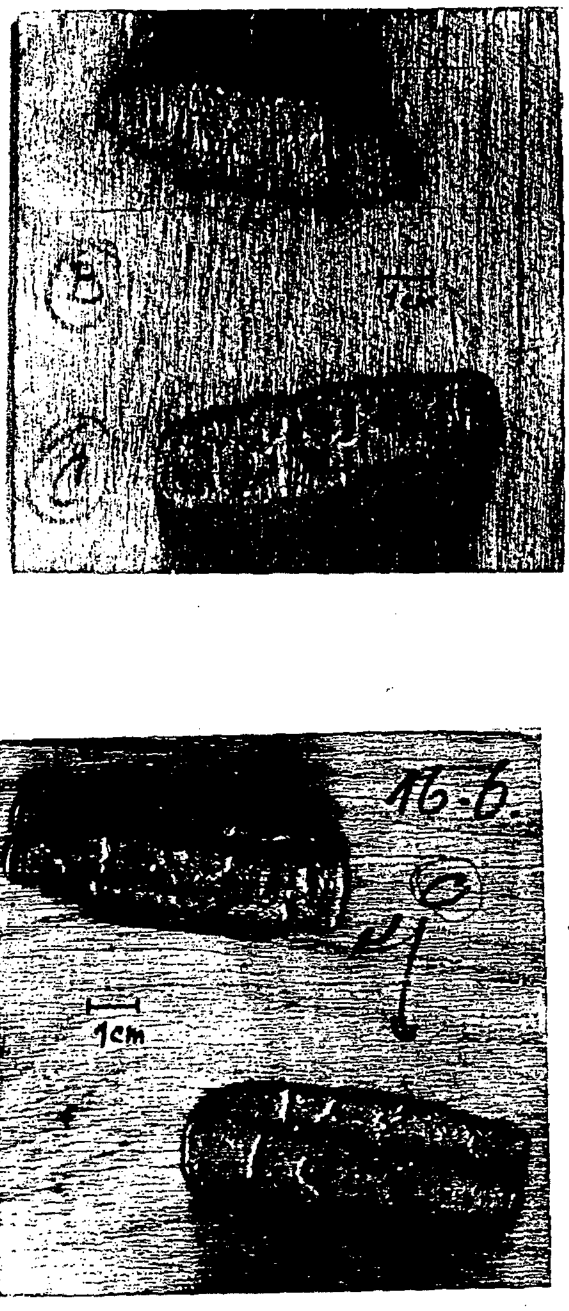
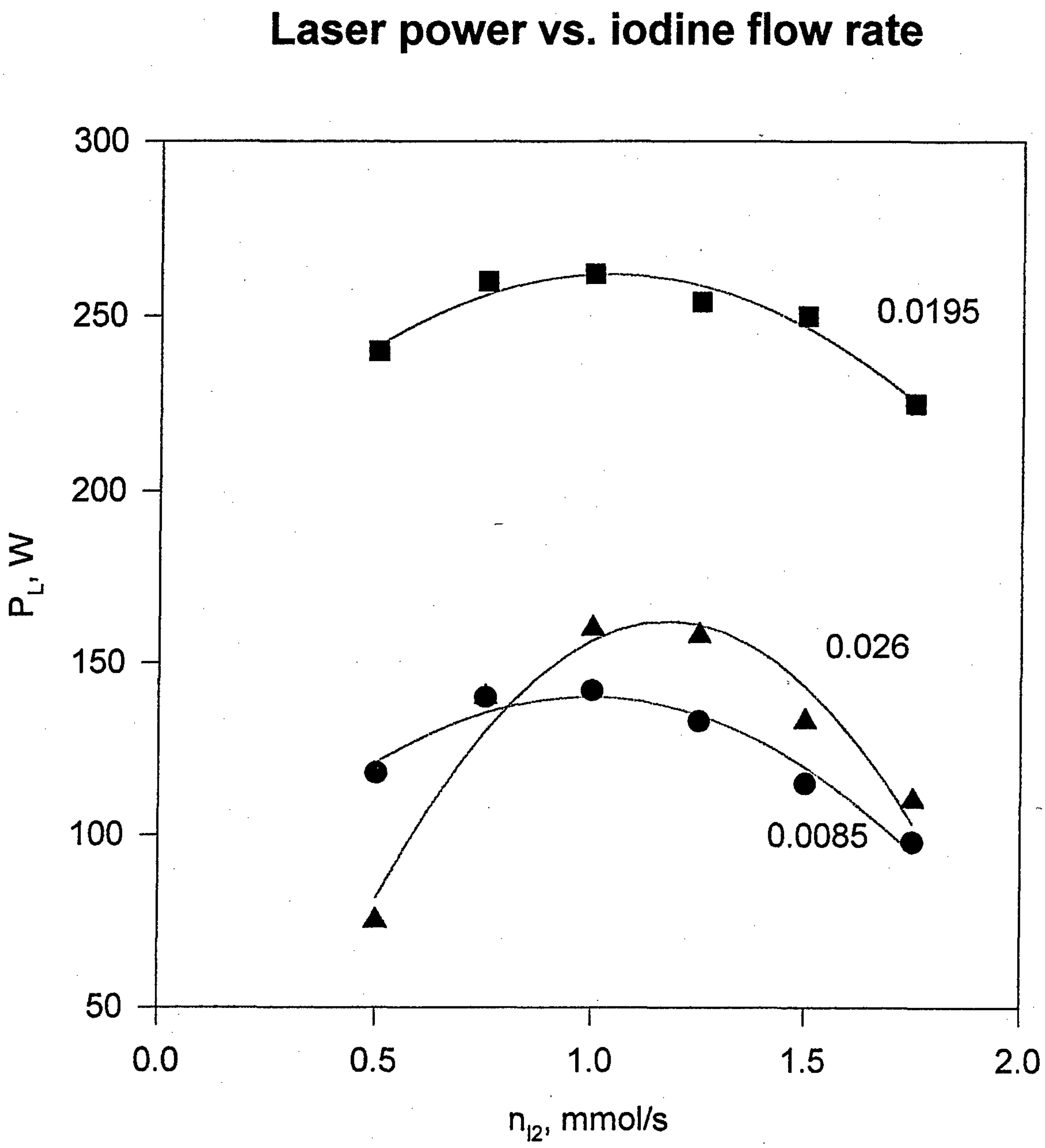


Fig. 5. Beam patterns on wood for laser power of 280 W

Fig. 6


Laser power vs. iodine flow rate
300
250
200
150
100
50
P_L, W
0.0
0.5
1.0
1.5
2.0
n_{I2}, mmol/s
0.0195
0.026
0.0085

Project Cost

1. Expendable supplies and materials:			$5,000
Gases and chemicals	$2,000		
Optical accessories (fibbers, wedge)	$2,000		
Data acquisition elements (electronics, software)	$1,000		
2. Equipment purchased:			$8,000
Valves (elmg) for aggressive medium (Burgert Cont.)	$1,500		
Flow meters for He and Cl_2 (Hennlich Insdustrietech.)	$1,500		
Laser Power Meter, LabMaster Ultima (Coherent)	$3,600		
CW Low Power Head, LM 100 (Coherent)	$1,400		
3. Travel – GCL/HPL conference, AFRL/DE visit:			$3,000
4. Publications, Reports, Literature purchased:			$1,000
5. Overhead charges:			$2,000
6. Labor-rewards:			$6,000
Dr Jarmila Kodymová (PI), senior scientist:	$1,800	900 hrs @$2,00/hr	
Dr Otomar Špalek, senior scientist:	$1,800	900 hrs @$2,00/hr	
Vít Jirásek, PhD student, junior scientist:	$500	500 hrs @$1,00/hr	
Dipl Ing Jan Kuželka, junior engineer	$900	900 hrs @$1,00/hr	
3 Technicians	$1000	1000 hrs@$1,00/hr	

Note: The above given amounts represents an extra money as the Institute of Physics supplements all workers by regular salaries. Senior scientists are paid by an average net salary (i.e. after a tax reduction) of $343/month, i.e. ~$2,00/hr, junior scientists and engineers by an average net salary of $170/month, i.e. ~ $1,00/hr, and technicians less than ~ $1,00/hr.

Total project cost **$25,000**